THERMAL SIMULATIONS WITH THESEUS-FE AND ANSA: OPTIMIZING THERMAL COMFORT IN AN OFFICE BUILDING ENVIRONMENT

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ABSTRACT –
THESEUS-FE is a thermal simulation package developed by P+Z Engineering GmbH, a leading supplier of engineering consultancy services in the automotive, aerospace, and general industry sectors. THESEUS-FE offers models for heat conduction, surface-to-surface radiation, simplified air zone and fluid volumes, as well as the human physiology and thermal comfort model FIALA-FE. For pre-processing tasks during the THESEUS-FE model creation process our customers and colleagues have long relied on the powerful features of ANSA. The recent development of a dedicated THESEUS-FE deck in ANSA has enabled new streamlined workflows where models can be transferred freely between ANSA and the THESEUS-FE graphical user interface without loss of information.

ANSA, with its strong focus on efficient mesh generation and numerous import and export functionality, has long been the strategic tool of choice in the THESEUS-FE community for preparing material and shell composite definitions, generating high-quality meshes, and defining sets for boundary conditions or thermal loads. Ideally, one single ANSA case serves as the basis for thermal simulations in THESEUS-FE, conjugate heat transfer simulations using OpenFOAM, or structural mechanics simulations for analysing thermomechanical problems using Abaqus.

In this paper we shall study an exemplary use case: quantifying and optimizing the thermal comfort of staff members working in an office building under intense solar loads. We will make heavy use of ANSA features for generating meshes, demonstrate the THESEUS-FE export feature, and completing the thermal simulation model in the THESEUS-FE GUI.

1. INTRODUCTION

In this study we will consider a building AC scenario for an office container under sunny summer conditions. We will study the effect of closing window blinds on the thermal comfort of three employees as well as the AC power consumption. This relatively simple and intuitive case serves to demonstrate the practical use of our thermal simulation software package THESEUS-FE and the pre-processing software ANSA (1) for creating optimization studies.

Figure 1 shows an overview of the relevant physics that determine the thermal behaviour of the office room system. We will model hypothetical environmental conditions corresponding to the date June 10th, 2015 for the location of Thessaloniki, Greece. The simulation will run from 09:00 to 18:00 local time. During this period the location of the sun will follow the true trajectory as observed on the ground, meaning that the direction of the direct solar beam radiation will change over time. In the afternoon hours significant levels of solar radiation will penetrate into the office container through the window on the west side. A movable window blind can be used to block the direct radiation. The room is also equipped with an air conditioning system to control temperature and humidity inside.

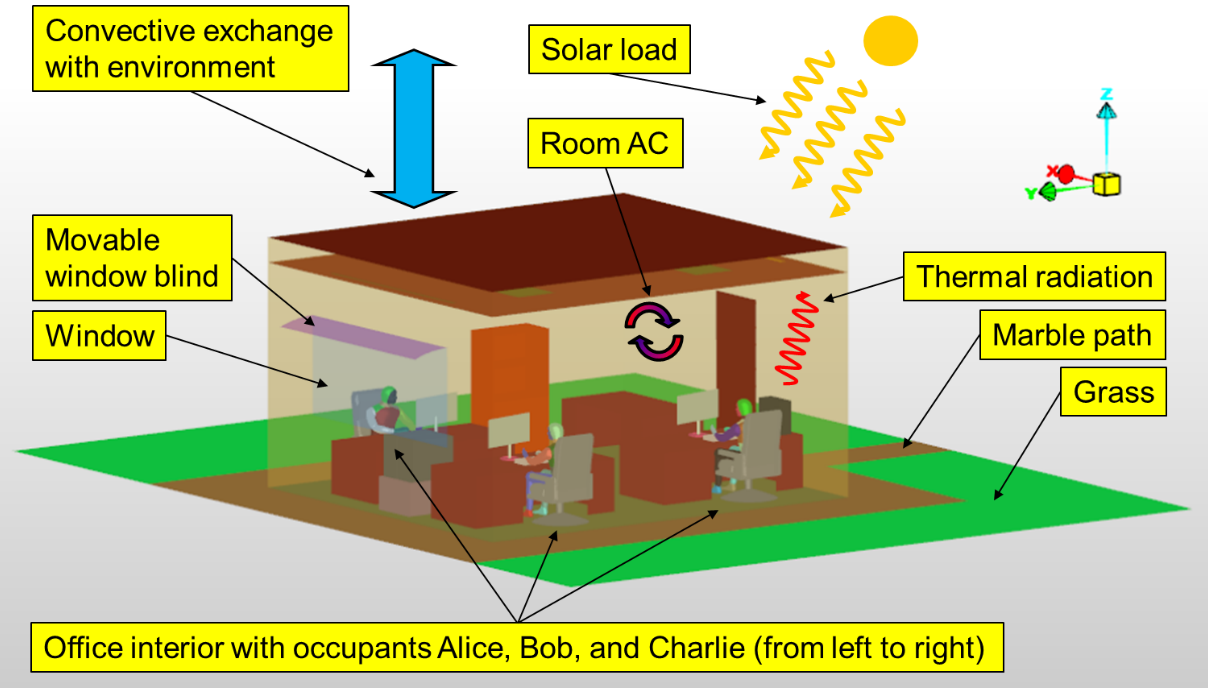

Figure 1: Office container and relevant physics

The thermal solver THESEUS-FE considers all relevant thermal effects for predicting the temperature over the course of the day:

- dynamic solar loads, short-wave transmission, reflection, and absorption
- thermal surface-to-surface radiation
- heat output from the personal computers used by the staff
- heat conduction through all solid parts
- simplified convective heat transfer between solid parts and air volumes
- effects of the air conditioning on the air inside the office
- full thermophysiological interaction of the virtual human manikin models for Alice, Bob, and Charlie with the air in the office

THESEUS-FE uses standard Nastran shell and solid elements for a simple discretization of the office components. Air volumes are modelled as thermodynamic reservoirs with a given volume and two degrees of freedom for the average temperature and humidity respectively. The human physiology model FIALA-FE used in THESEUS-FE is based on the well-known and established Fiala model described in (2) and (3). THESEUS-FE is capable of computing local and global measures of thermal comfort such as equivalent temperatures, Berkeley thermal sensation and comfort, or Predicted Mean Vote (PMV). In this study we will use PMV values reported by Alice, Bob, and Charlie as a simple global measure of comfort.

2. DETAILS OF THE CONSIDERED SCENARIOS

Environmental conditions

For simulations incorporating thermal exchange with a natural environment, THESEUS-FE makes use of the following conventions regarding the global coordinate system: The x-coordinate direction points due North, the y-coordinate is West, and the z-coordinate points toward the zenith. The sun acts a source of parallel short-wave radiation with a defined time-dependent intensity for the direct beam radiation, see. In addition to the direct beam radiation there is also a diffuse component as shown in
Figure **2**. The direction of the direct radiation is measured using two angles: solar altitude and azimuth, as explained in
Figure **3**. Figure 4 shows plots of altitude and azimuth angle over time.

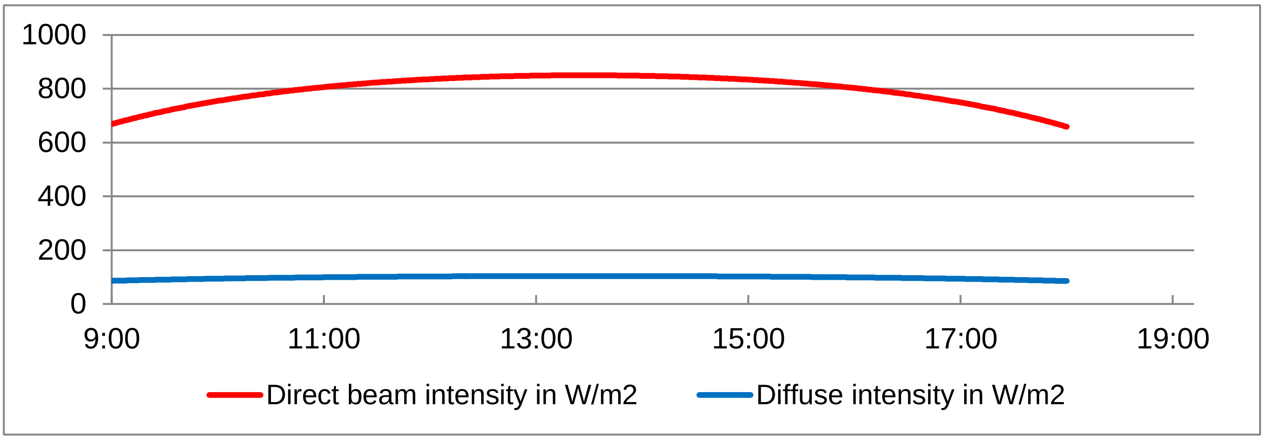

Figure 2: Direct and diffuse solar intensity over time

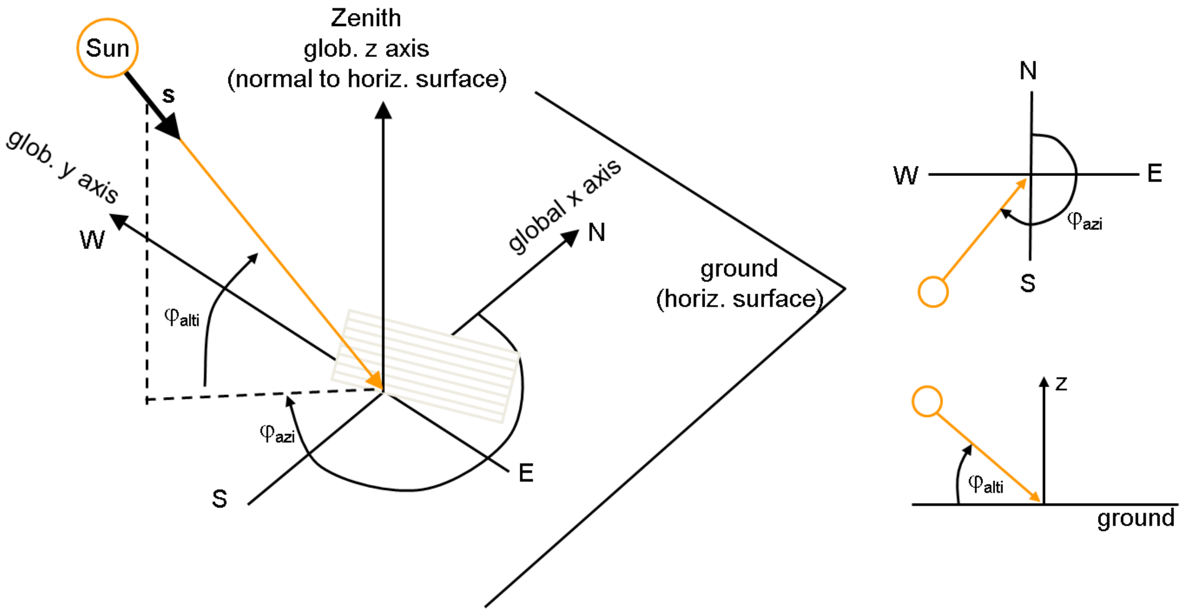

Figure 3: Definition of solar azimuth and altitude

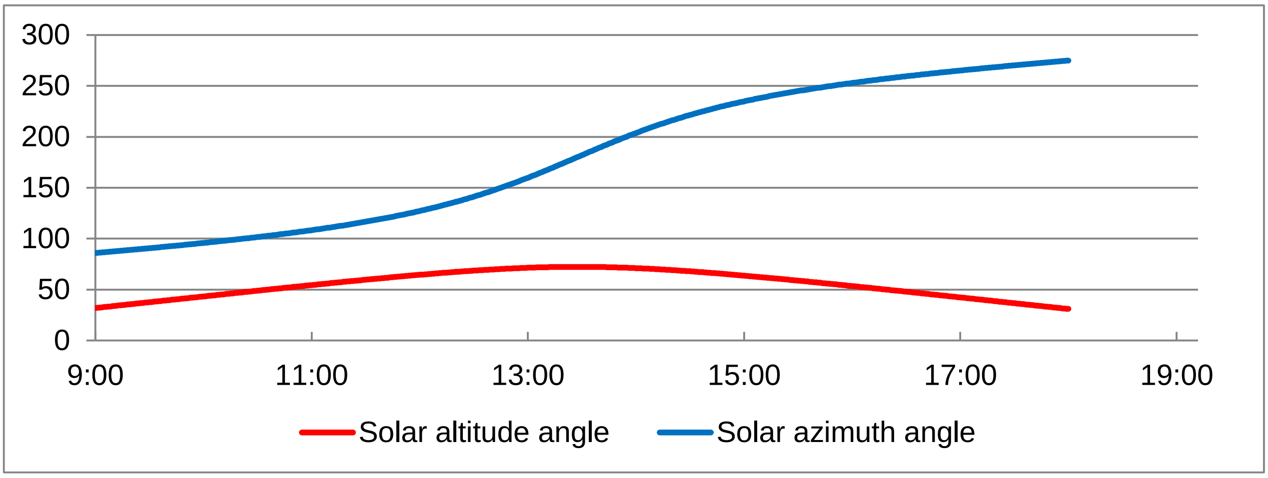

Figure 4: Solar altitude and azimuth angles over time

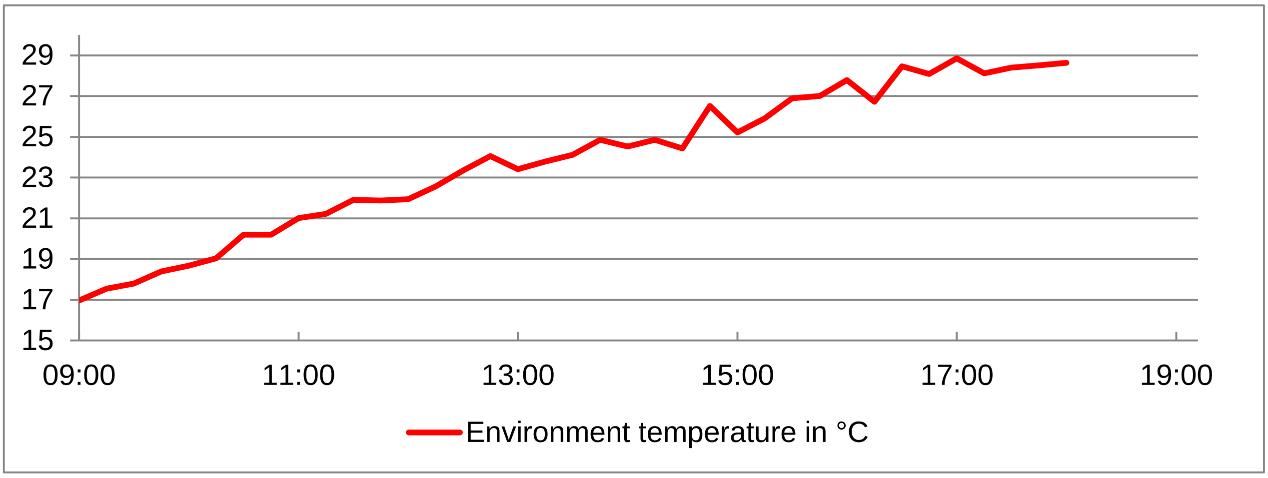

Figure 5: Environment temperature over time

The environment air temperature is also specified as a function over time, see Figure 5. Using a given constant wind speed of 1 m/s the solver computes an effective heat transfer coefficient that governs the convective heat exchange between outside air and the exterior surfaces.

Human manikin and thermal comfort modelling

The office interior contains three staff members Alice, Bob, and Charlie. These are modelled using the THESEUS-FE virtual manikin model FIALA-FE. FIALA-FE takes into account both the active and passive system of human thermoregulation. Heat conduction inside the body is described by a number of specialized cylindrical and spherical finite elements as shown in Figure 6. This leads to a comparatively low number (about 500 per manikin) of degrees of freedom to describe the thermal state of each manikin. The manikin internal thermal model couples to the office environment via a detailed shell model, seen left in Figure 6. The shell model acts as an interface for radiative and convective heat transfer, and can also be defined to enter into thermal contact with furniture objects such as seats.

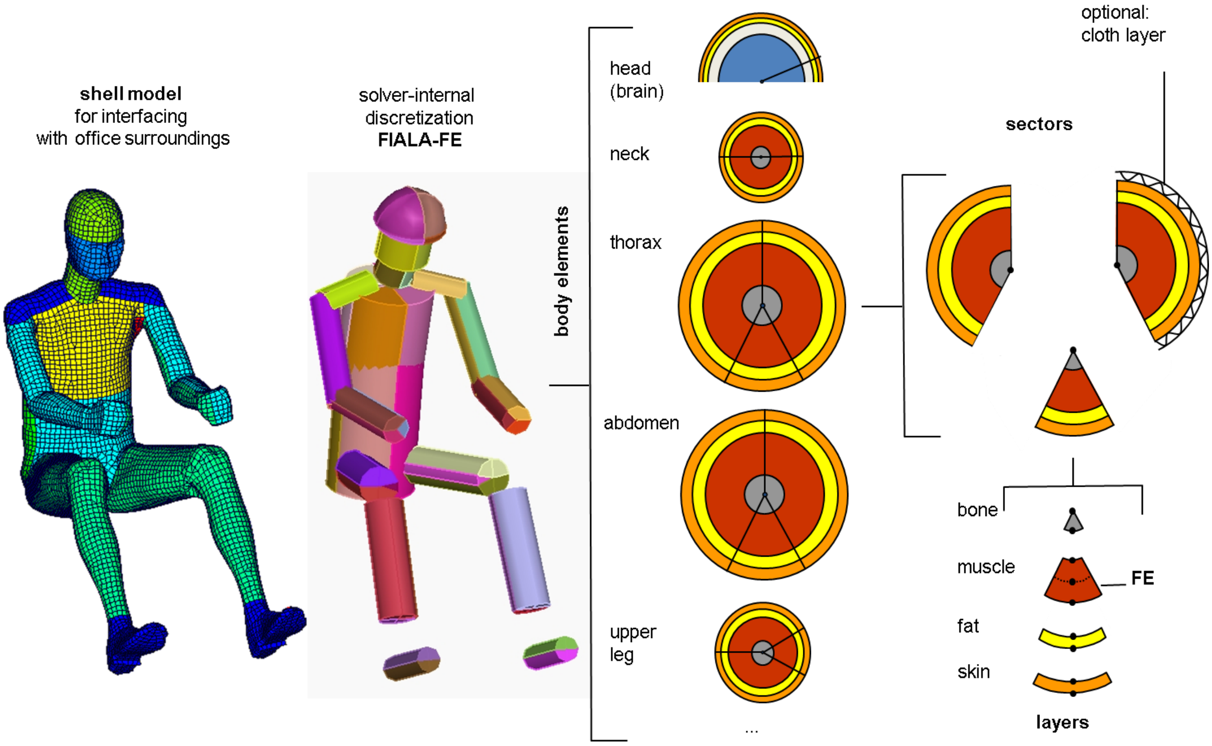

Figure 6: Principles of the thermal manikin model FIALA-FE

As stated above, we use the Predicted Mean Vote (PMV) index defined in (4):

$$PMV = f(R_{cl}, M, T_{air}, T_{rad}, v_{air}, p_{air,w})$$

The variables used are

- R_{cl} : Global thermal resistance of clothing in m^2K/W
- M : Metabolic rate in W/m^2, defined by the level of activity of the manikin
- T_{air} : Mean air temperature surrounding the manikin in °C
- T_{rad} : Mean radiant temperature as experienced by the manikin in °C
- v_{air} : Mean air velocity in m/s
- $p_{air,w}$: Partial water vapour pressure surrounding the manikin in Pa

The output of the PMV formula is an index characterizing the thermal comfort according to the 7-point ASHRAE scale ranging from -3 (cold) through 0 (ideal, neutral) to +3 (hot).

Interior conditions

The air inside the office is modelled using a so-called airzone object in THESEUS-FE. The airzone object describes a given constant volume of 62 m^3 of air. The pressure is fixed at 101300 Pa while average temperature and relative humidity are treated as degrees of freedom. The airzone temperature and humidity are influenced by three mechanisms:

- convective heat exchange with surrounding walls
- convective heat exchange and steam input from the manikin models
- heating or cooling from the AC system

We prescribe a constant air speed of 0.1 m/s inside the office environment. Again, the solver translates the given wind speed into an effective heat transfer coefficient to control the convective exchange with walls. The manikins Alice, Bob, and Charlie also act as steam sources through respiration and transpiration.

The AC system is assumed to act in recirculation mode, without fresh air input from the environment. When active, it will cool a fixed volume flow of 288 m^3/h. In THESEUS-FE there are various options for setting the AC outlet temperature. Besides specifying given outlet temperatures as given time-dependent curves or by assigning a constant cooling power to the AC system, there is the possibility of specifying the outlet temperature to yield a constant average PMV value for the manikins. In detail this process entails the following calculations: the PMV thermal comfort value is a function of the airzone temperature, as described above. By inverting this functional relationship, we can determine the necessary airzone temperature to achieve a desired PMV. The AC outlet temperature can in turn be set to achieve the necessary airzone temperature at any moment in time.

Considered variants

Simulations were carried out for the following four scenarios:

- Variant 1: window blind open, air conditioning off
- Variant 2: window blind closed, air conditioning off
- Variant 3: window blind open, PMV-targeted air condition on
- Variant 4: window blind closed, PMV-targeted air condition on

For all four variants we will compare the achieved PMV comfort values as well as the AC cooling power.

3. WORKFLOW USING ANSA AND THESEUS-FE

Mesh generation and general pre-processing for THESEUS-FE simulation cases is easily done within ANSA. In the past, our customers made use of the NASTRAN deck in ANSA and

exported an MSC Nastran deck containing the basic finite element mesh, as well as property and material definitions. This is possible since the THESEUS-FE case definition syntax is an extension of a subset of MSC Nastran. For example, a CTRIA linear triangular finite element is directly usable for THESEUS-FE.
Recent versions of ANSA, starting with v14.*, have introduced a dedicated THESEUS-FE deck. It offers all the features for defining the bulk of a THESEUS-FE case, including boundary conditions, radiation properties, and simple fluid objects such as the airzones described above. At any given point, the ANSA database can be output as a THESEUS-FE case and opened in the THESEUS-FE GUI where one can complete or adjust the model definitions. It is not planned nor is it desirable or necessary that a complete THESEUS-FE simulation case is defined within ANSA – this would entail too much maintenance effort as new features arise in THESEUS-FE that would need to be incorporated within ANSA. Instead, the current approach offers the best of both worlds, since ANSA is already very strong at tasks our customers require every day, e.g.

- converting CAD definitions or foreign simulation models into the required format
- creating high quality surface or volume meshes
- dealing with highly complex and large cases

The THESEUS-FE GUI and Solver development can then focus on our core business: creating simulation capability for highly efficient thermal modelling.

The office container model described in this paper started life as a simple CAD model in ANSA, see Figure 7. The human manikin models are not yet included in the model.

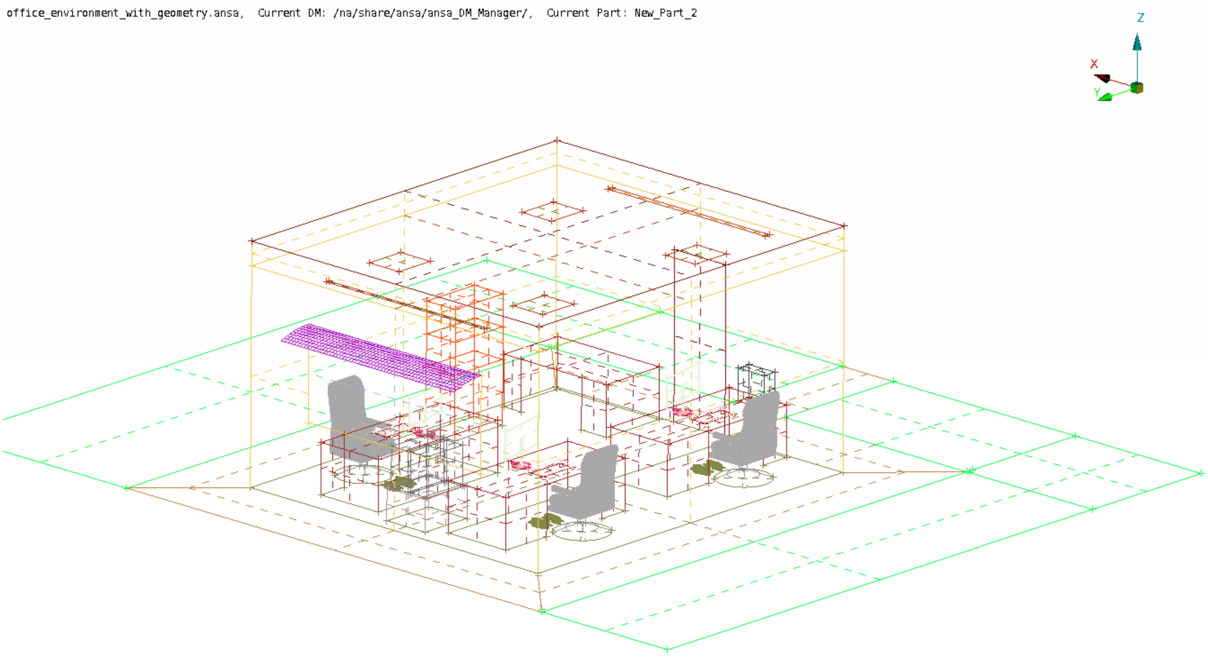

Figure 7: CAD model of the office container in ANSA

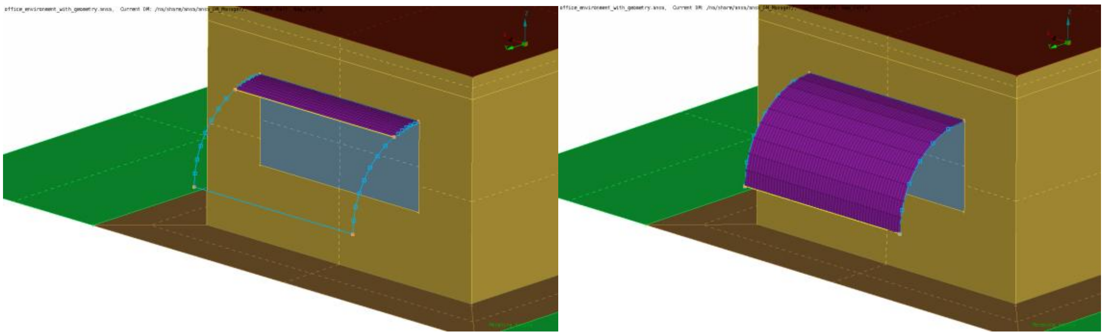

Figure 8: Parametrized movement of the window blind

The position of the window blind was parametrized using a 2D morphing box in ANSA. This makes it possible to change the geometry between the two defined states “up” and “down” with maximal ease, confer Figure 8.

Most of the boundary conditions, all of the property and material definitions, the airzone object, as well as the tabular data describing the sun position and intensity over time are already defined in the ANSA case. The tabular data itself was generated using the EnvironmentGenerator tool in the THESEUS-FE GUI and transferred via a simple copy-and-paste into ANSA. We then exported two THESEUS-FE models corresponding to the states “window blind up” and “window blind down”.

On the THESEUS-FE side we defined the remaining model parts, including the manikin geometry, the solver definitions, and the AC definitions. These were saved as a separate model case file named `additional_definitions.tfe`, see Figure 9. For each of the four variants defined in the prior section we created a small THESEUS-FE case file using INCLUDE statements to reference model definitions from other files and combine everything into the final case, ready for passing to the THESEUS-FE solver. For example, Variant 1 is defined the file `office_environment_complete_01.tfe` containing just these definitions:

```
INCLUDE from_ANSA_01.tfe
INCLUDE additional_definitions.tfe
```

This modular strategy makes it very easy to efficiently change only the necessary parts of the model and avoids wasting disk space by storing redundant large mesh definitions in multiple files. Note that this workflow is easily automated by making use of the powerful Python scripting capabilities either within ANSA or using standalone Python scripts to generate model parts. Since the THESEUS-FE decks are stored in a well-documented ASCII-based format, it is very easy to create scripts that automatically modify or generate decks.

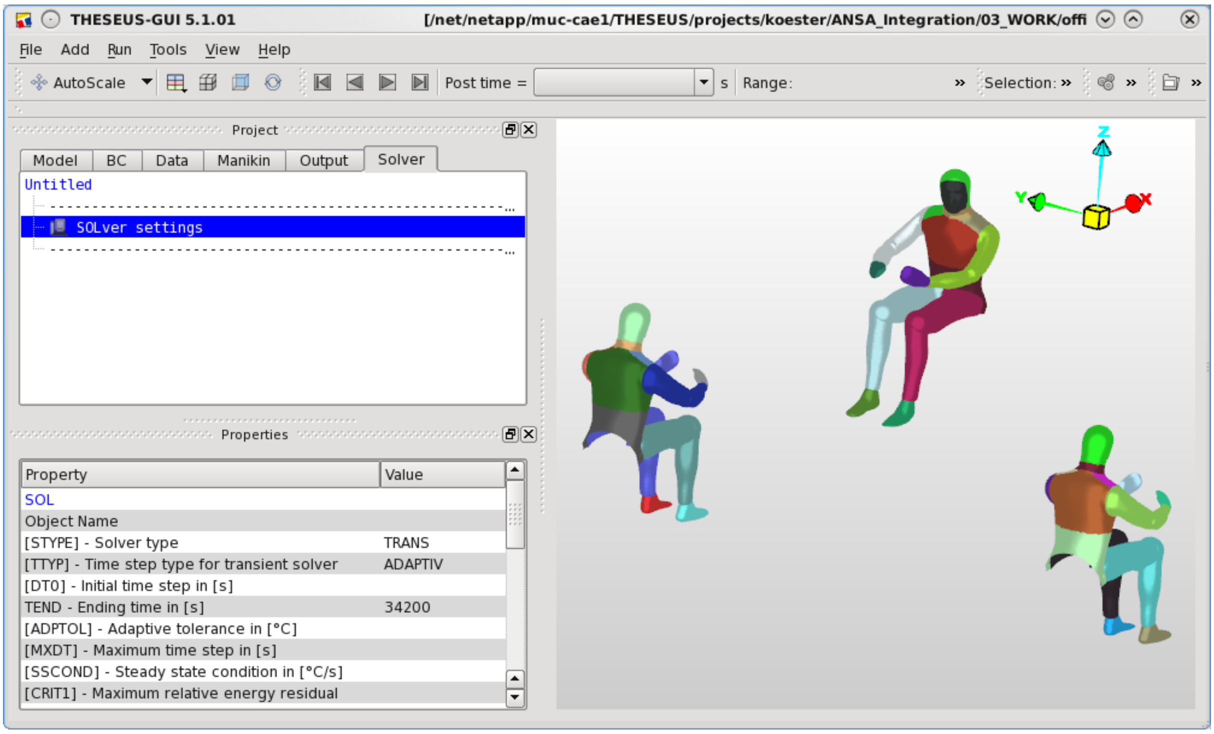

Figure 9: Case components defined within the THESEUS-FE GUI: manikins, post-processing, and solver definitions

4. RESULTS AND CONCLUSIONS

For each of the four variants we perform one solver run. On a modern machine this will take between 1 to 3 hours of wall clock time.

Variant 1: window blind open, air conditioning off
Figure 10 presents the airzone temperature within the office container over the simulated period; Figure 11 shows the PMV index over time for Alice, Bob, and Charlie. Towards the end of the day, the sun will shine through the window on the west side of the container, causing Bob to feel too warm, see Figure 12.

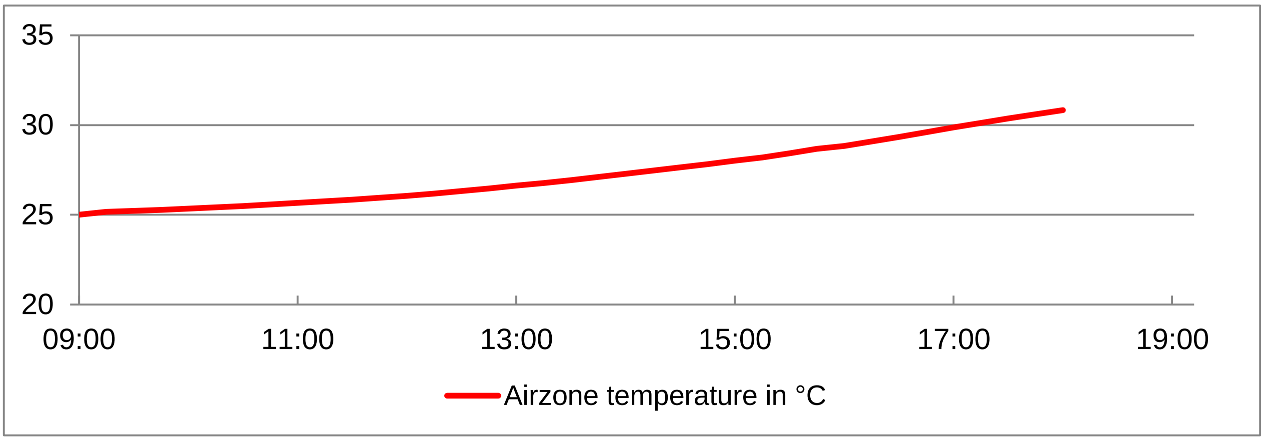

Figure 10: Average air temperature within the office container

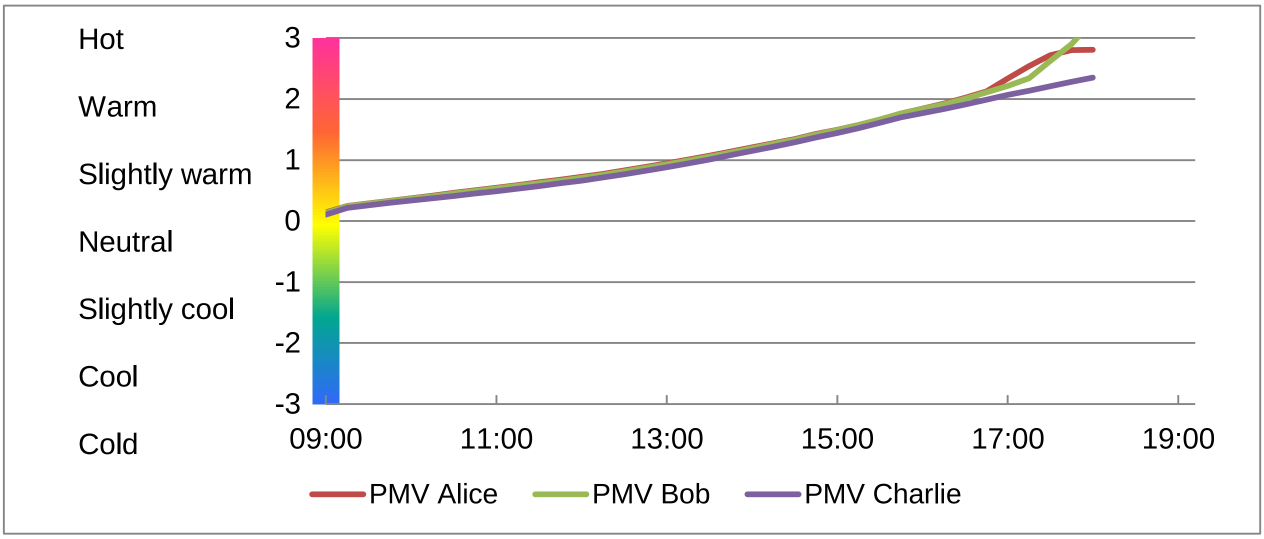

Figure 11: Predicted Mean Vote for all three building occupants

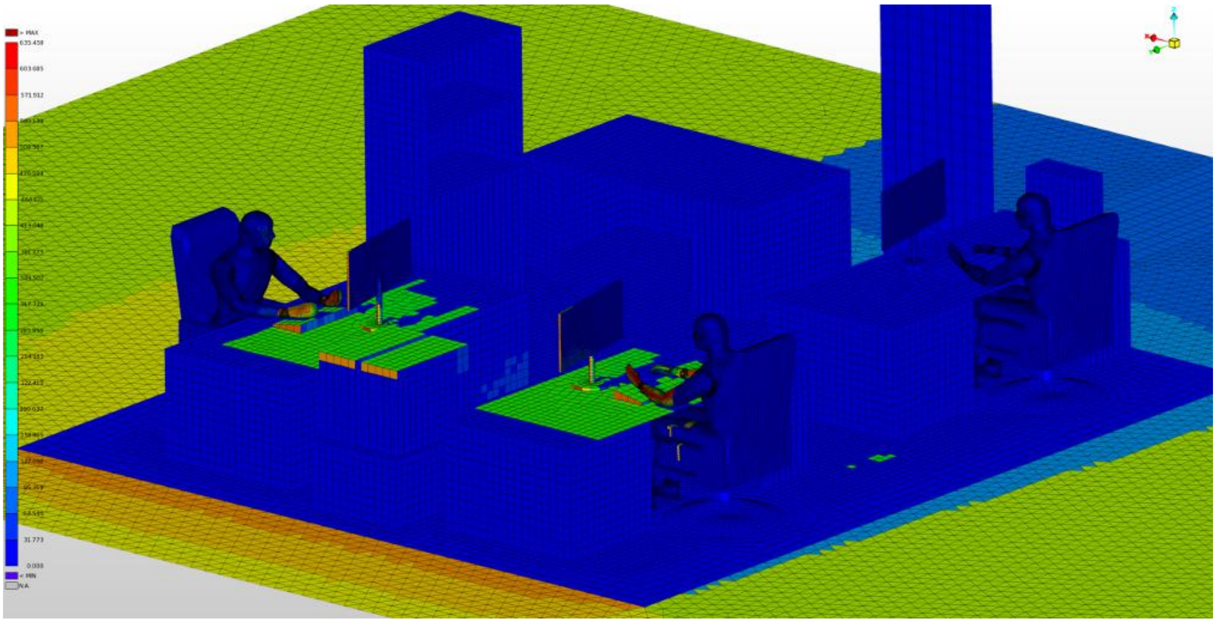

Figure 12: Solar irradiation at 18:00. Bob in the middle receives direct sunlight on his lower arms, resulting in off-the-scale PMV values.

Variant 2: window blind closed, air conditioning off

Closing the window blind naturally prevents the direct penetration of sunlight into the office. This leads to slightly lower air temperatures at the end of the day and improved comfort values of “warm” instead of “hot”, see Figure 13 and Figure 14. The solar irradiation at 18:00 is shown in Figure 15.

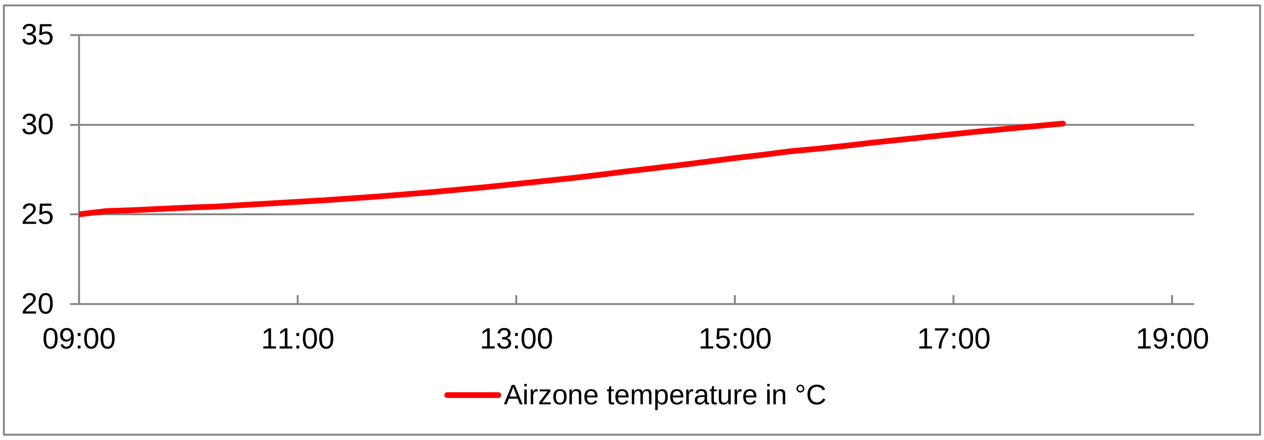

Figure 13: air temperature in the office with blind closed

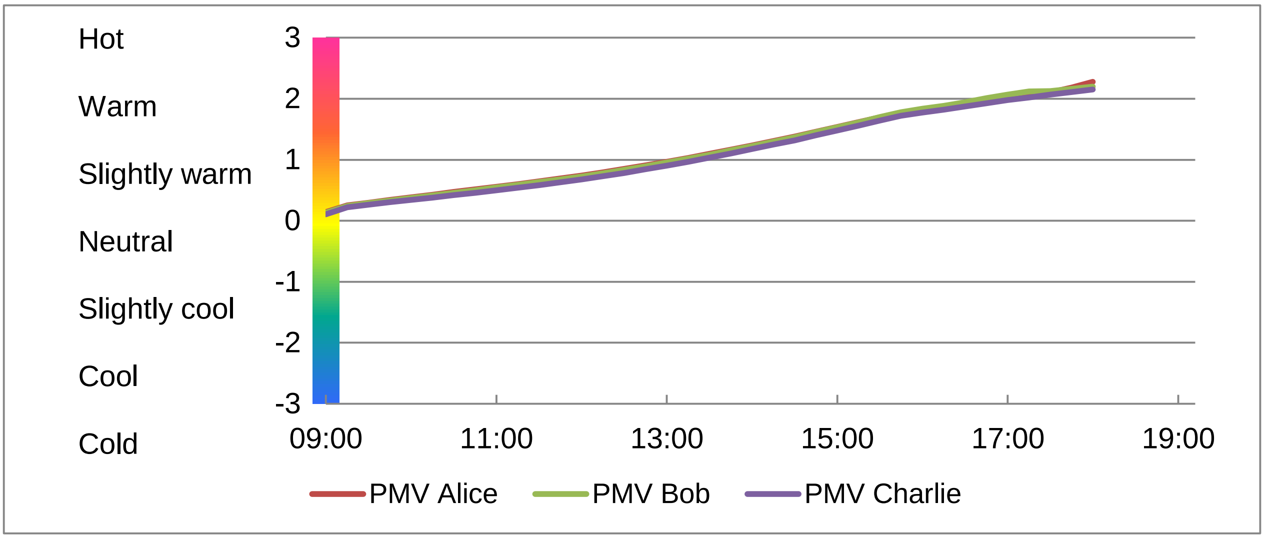

Figure 14: PMV values with blind closed

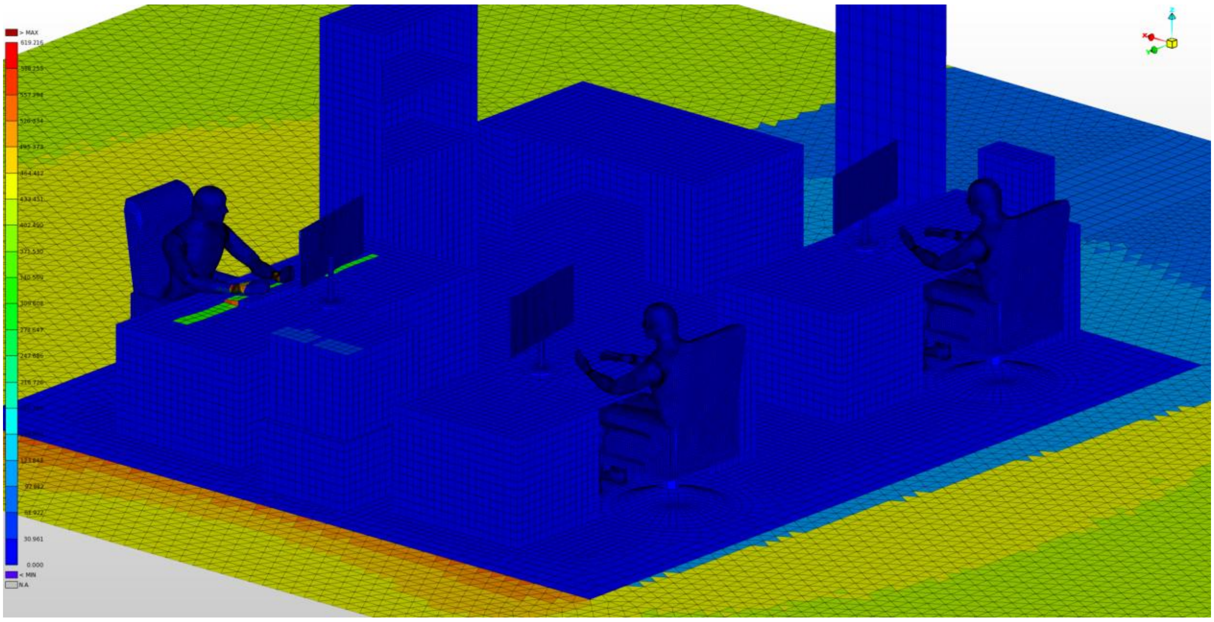

Figure 15: Solar irradiation at 18:00, blind closed. Almost no sunlight reaches the office in this case.

Variant 3: window blind open, PMV-targeted air condition on

We are back in the situation of Variant 1 - the window blind is open, allowing significant levels of solar radiation to penetrate into the office in the late afternoon hours. However, this time the AC is on and the outlet temperature set to maintain ideal comfort as measured by the average PMV value. The office and AC outlet temperatures are shown in Figure 16. Note that very low outlet temperatures needed to hold a comfortable office temperature of around 22 °C. It would probably be better in practice to raise the volume flow of the AC instead.

The PMV values are mostly pegged at zero for most of the day. Things get interesting for Bob in the late hours of the afternoon where the sunlight reaches his forearms. His PMV value rises, forcing the AC outlet temperature down to compensate. Charlie is sitting in the shade for the entire time and feels too cold.

Finally, Figure 18 shows the necessary AC cooling power over the day.

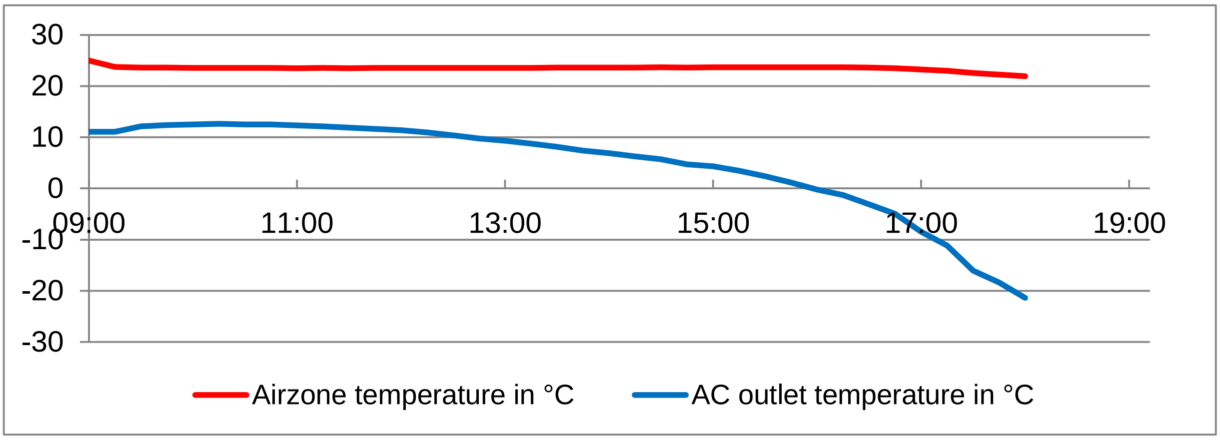

Figure 16: Airzone and outlet temperature with blind open

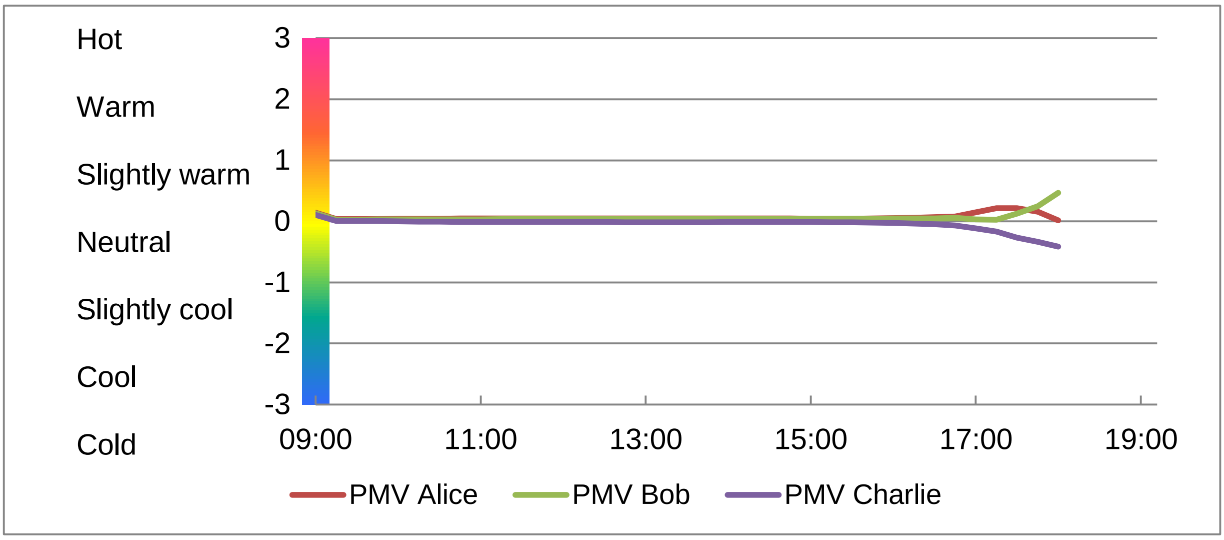

Figure 17: PMV values for all three occupants with blind open

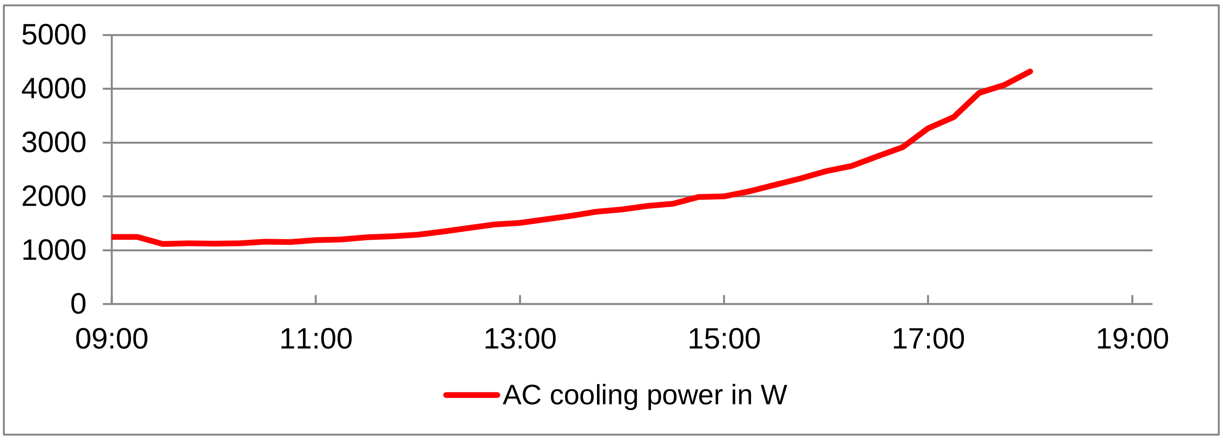

Figure 18: AC cooling power with blind up and AC on.

Variant 4: window blind closed, PMV-targeted air condition on

The blind is now closed and the AC is on. This situation guarantees optimal comfort (see Figure 20) over the entire day. As shown in Figure 19 the AC outlet temperature does not need to drop as low as in Variant 3, while the room temperature practically remains constant. The higher AC outlet temperature translates to lower power consumption (Figure 21).

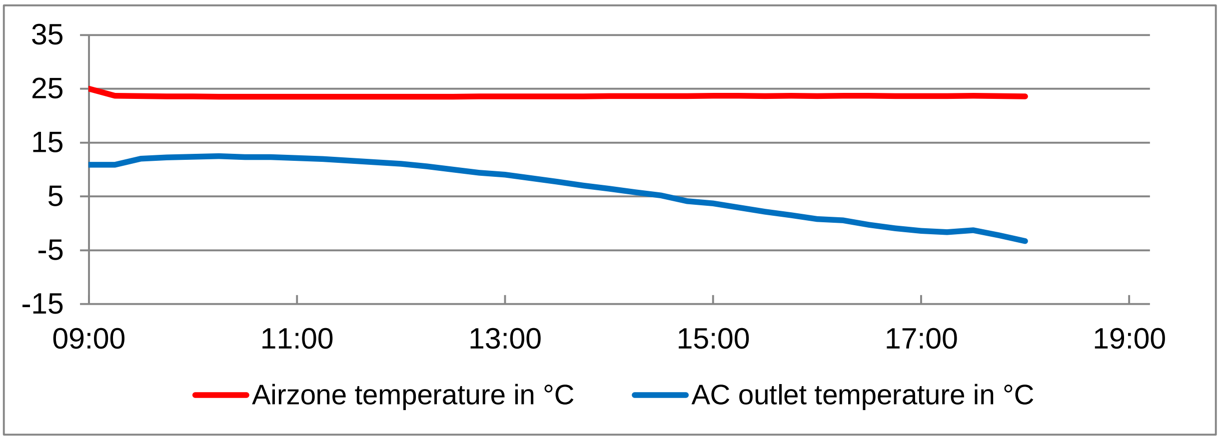

Figure 19: Office and AC outlet temperature with blind down and AC on

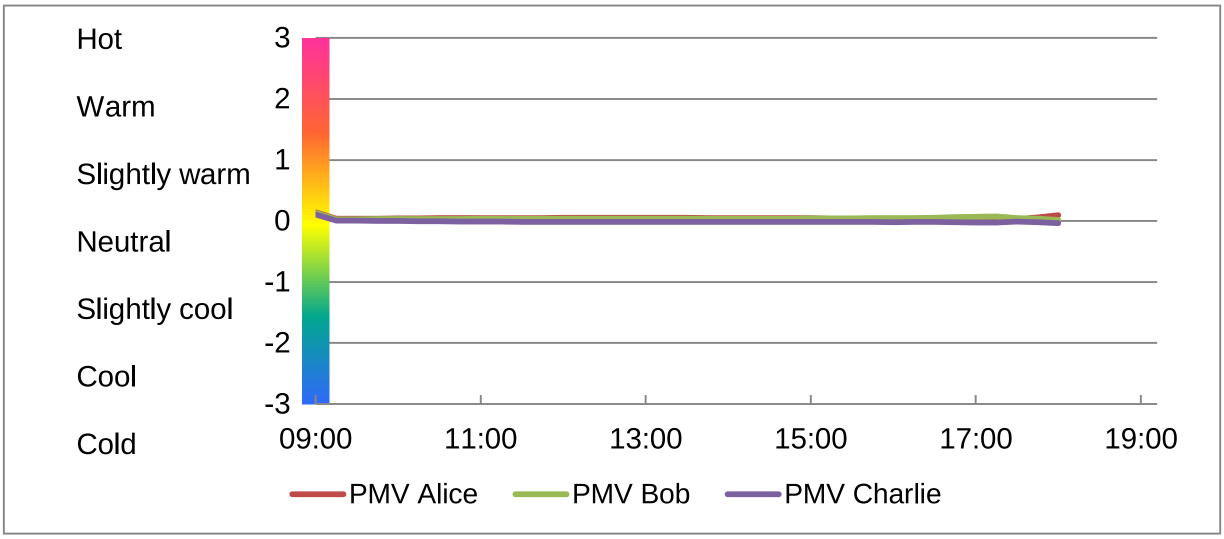

Figure 20: PMV values for blind down and AC on

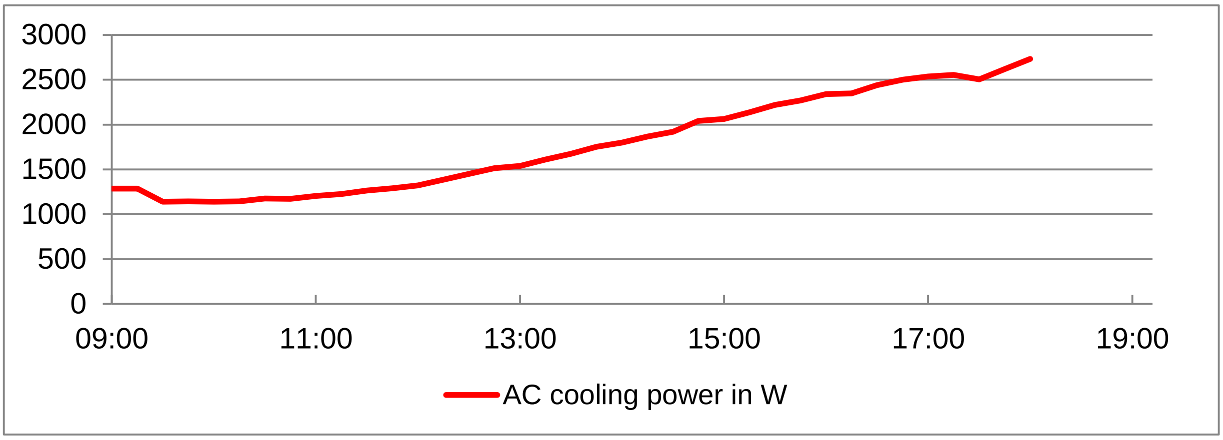

Figure 21: AC cooling power for blind down

Conclusions

We have demonstrated a simple use case for combining the pre-processing power of ANSA with the thermal simulation capability of THESEUS-FE. The techniques employed lend themselves to automation, e.g. using Python scripts.

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